Pupil Planes versus Image Planes
Comparison of beam combining concepts

John Young
University of Cambridge

Outline

- Aims of this presentation
- Beam combiner functions
- Image plane vs Pupil plane
- Multiplexing multiple baselines
  - Cross-talk
- Field of View Issues
- Summary

Aims of Presentation

I am aiming to get across the following:

- Common features of image plane and pupil plane combination
- Differences
- Trades-off in combiner design
- Some instrument-related issues in interpreting visibility data

Beam Combiner Functions

- Generate fringe pattern(s) suitable for recording with detectors
- Want fringes on many interferometer baselines
  – Amplitude and phase of fringes on each baseline encode amplitude and phase of one Fourier component of source brightness distribution
- Want high-signal-to-noise fringes
  – Small collectors, low throughput; hence few photons
  – Atmosphere usually forces short integration times
- Since we cannot coherently amplify our signals, the previous two requirements usually conflict

Beam Combination

- The essential principle here is:
- Add the E fields, E_1+E_2, and then detect the time averaged intensity:

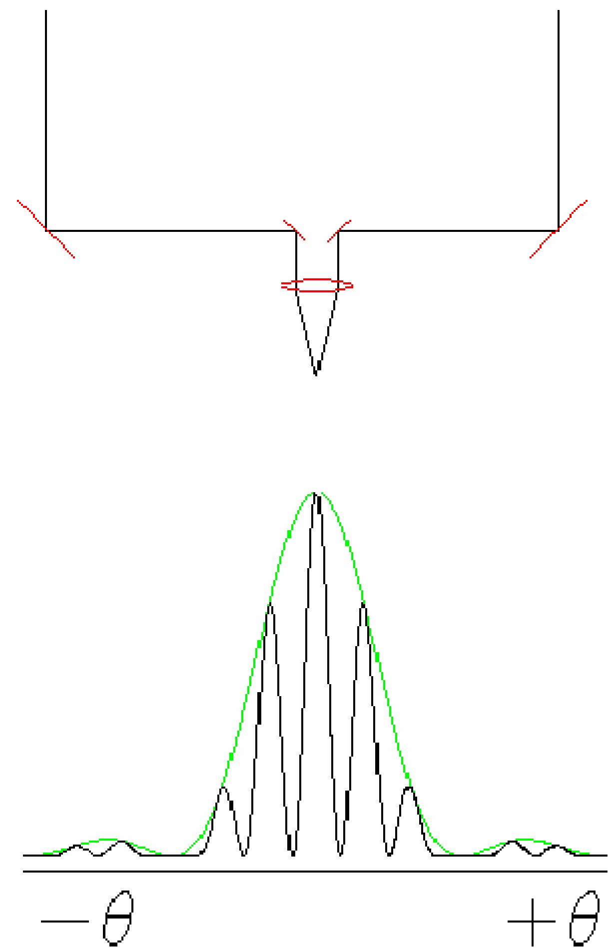
$$\langle(E_1+E_2)(E_1+E_2)^*\rangle = \langle|E_1|^2\rangle + \langle|E_2|^2\rangle + \langle E_1E_2^*\rangle + \langle E_2E_1^*\rangle$$
$$= \langle\, |E_1|^2\rangle + \langle\, |E_2|^2\rangle + \langle\, 2|E_1||E_2| \cos\varphi\rangle$$

  where φ is the phase difference between E_1 and E_2

- In practice there are two straightforward ways of doing this:
  - Image plane combination:
    - e.g. AMBER (VLTI), MIRC (CHARA), aperture masking experiments
  - Pupil plane combination:
    - e.g. NPOI, IOTA

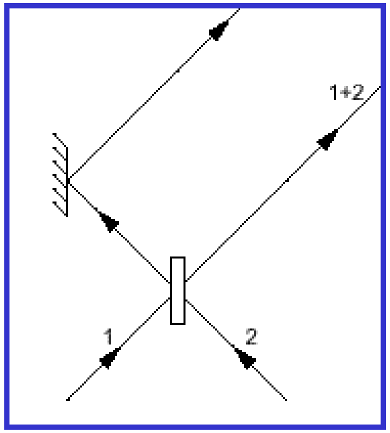
Image Plane (Multi-Axial) Combination

- Mix the signals in a focal plane as in a Young's slit experiment:
- In the focused image the transverse co-ordinate measures the delay
- Fringes encoded by use of a non-redundant "input" pupil
- Possible to use dispersion prior to detection in the direction perpendicular to the fringes

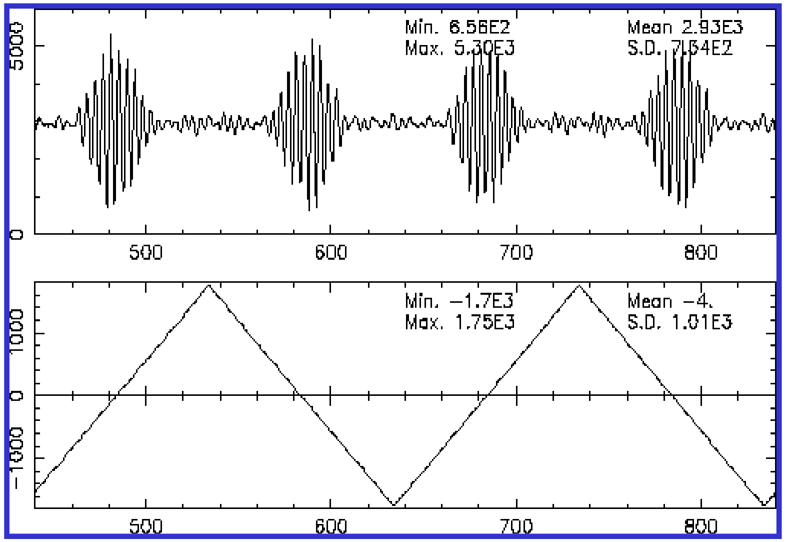


Pupil Plane (Co-Axial) Combination

- Mix the signals by superposing **afocal** beams:

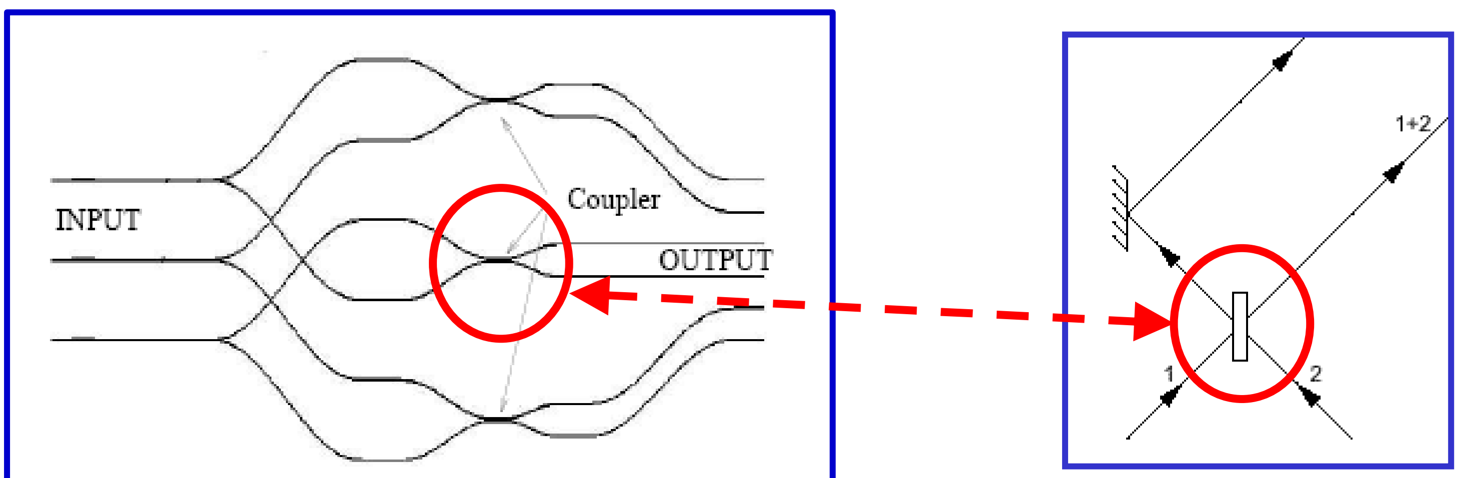


- Focus superposed beams onto a single element detector
- Fringes encoded by use of a non-redundant modulation of delay of each beam
- Fringes are recorded by measuring intensity versus time
- Spectral dispersion can be used prior to detection



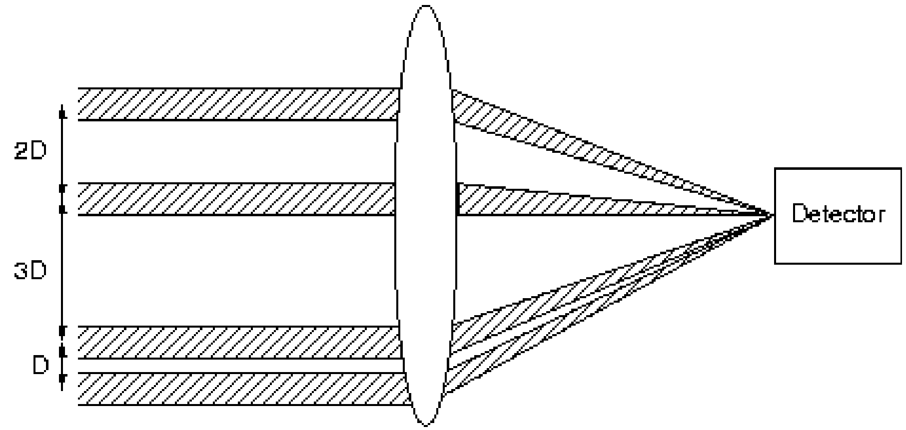
Integrated Optics Combiners/Fibre Couplers

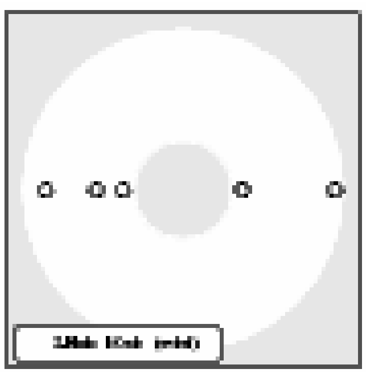
- Co-axial combination in a waveguide
- Single-mode waveguide performs spatial filtering “for free”
- Everything I will say about “pupil plane” combination (usually refers to free-space co-axial combination) applies equally to IO unless otherwise stated
  - IO facilitates using static delays to encode fringes, rather than active modulation

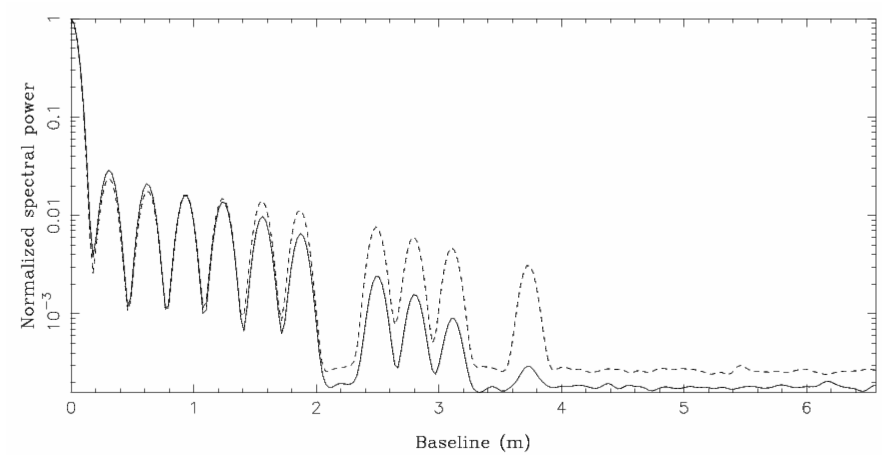


Multiplexing – Image Plane

- Use non-redundant “input” pupil
- 1d pupil allows spectral dispersion perpendicular to fringes
- 2d pupil requires fewer detector pixels per baseline
- Possible to use optical fibres to remap pupil

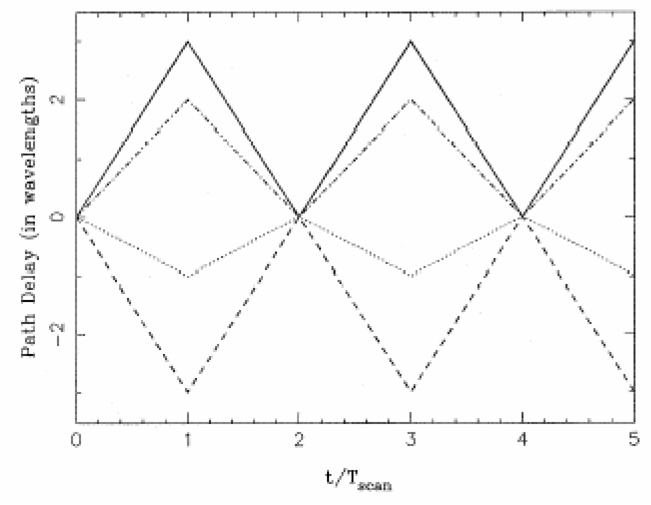


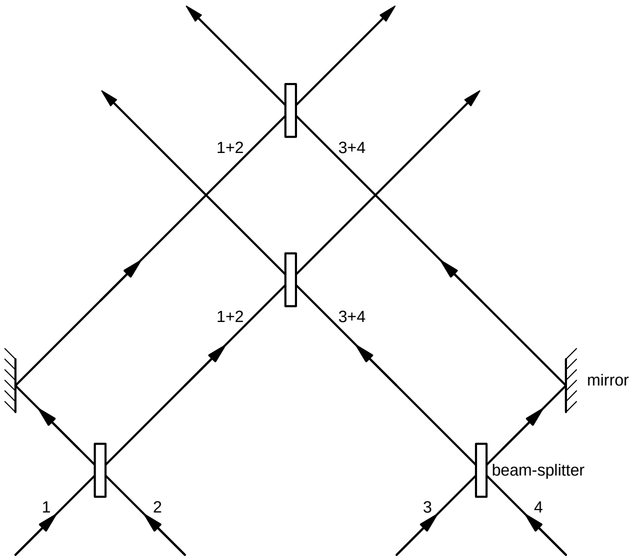




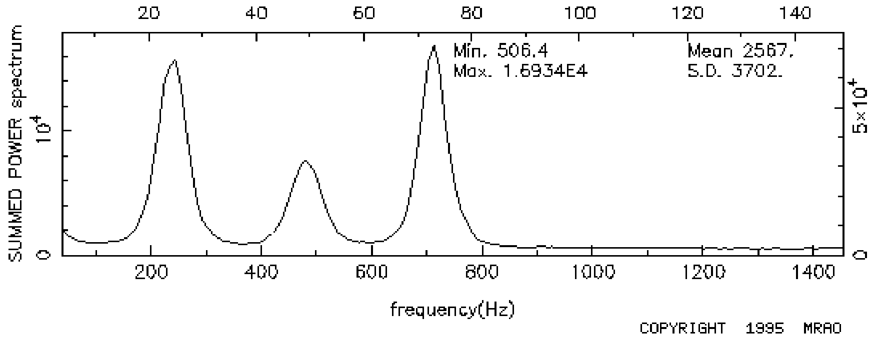
Multiplexing – Pupil Plane

- Mix beams at successive beam-splitters (couplers)
- Modulate delays of input beams so that each baseline has a unique net velocity



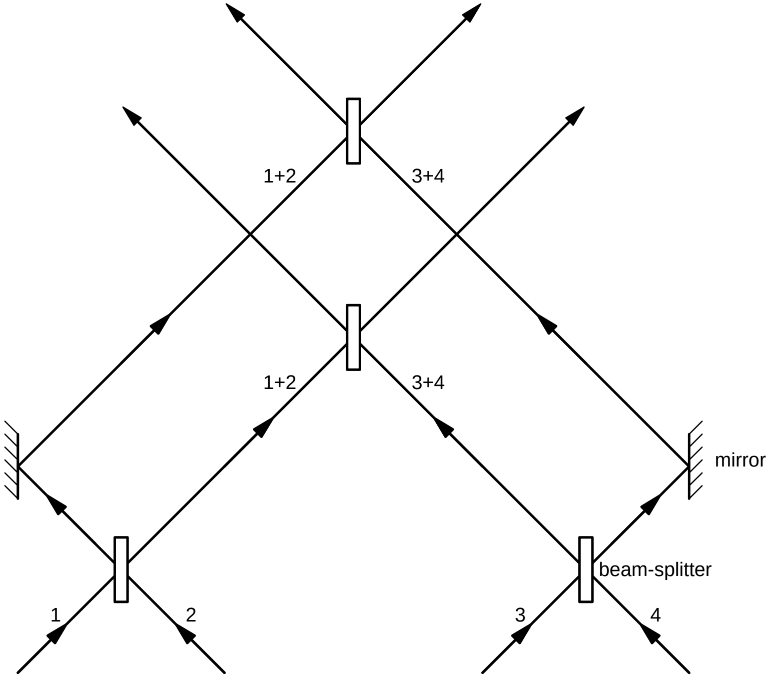


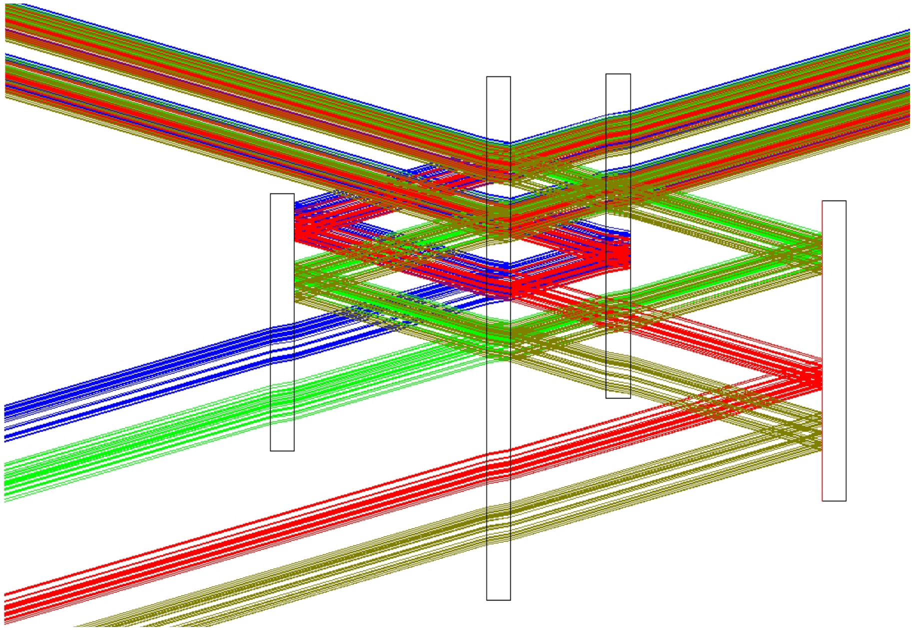
- Fringe signal then appears at unique frequency for each baseline



Multiplexing – Pupil Plane

- Can use symmetry to decrease number of optical components
- The combiners below are functionally equivalent
  - Apart from angles of incidence



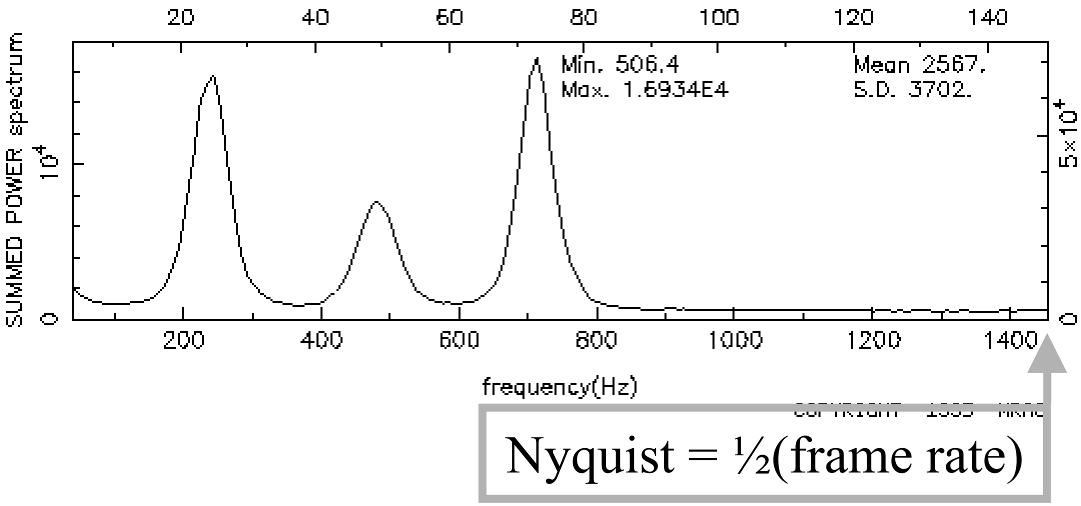


Signal-to-Noise Comparison

- Buscher (1988) showed that (all-one-one) pupil-plane and image-plane implementations give identical signal-to-noise, provided:
  - Noise-free detector
  - Fringe scanned in << t_0
  - Can coherently combine signals from all outputs of pupil-plane combiner
- Choice driven by practical considerations
  - Detector format & performance
  - Cost of detector(s)
  - Cross-talk/calibration
  - Alignment/stability
  - Spectral bandwidth

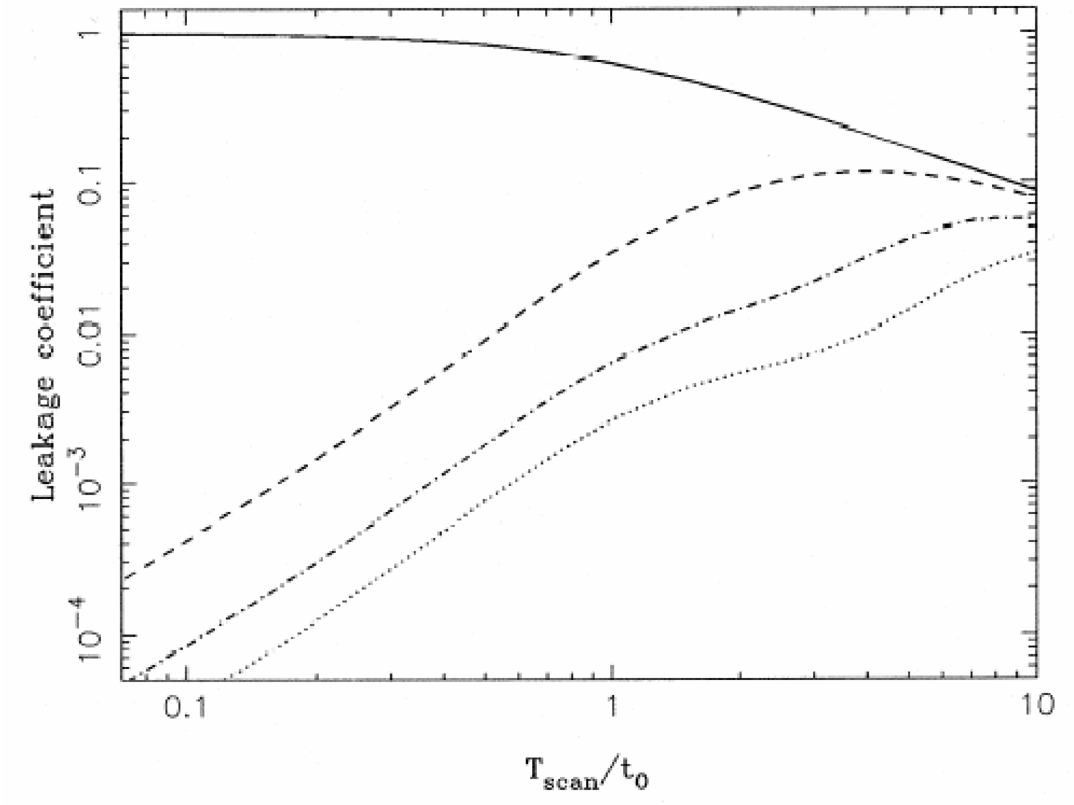
Crosstalk – Pupil Plane

- Delays of input beams are also being changed by atmosphere
  - Perhaps just residual from external fringe tracking
- This perturbs delay velocities
  - Smears fringe signal in frequency space
  - Peaks in power spectrum are broadened – can overlap unless fringe frequencies are well-separated => **fast modulators and detectors**
- Non-linear modulation also causes cross-talk
  - Mitigate with novel demodulation algorithms – see Thorsteinsson & Buscher (2004)

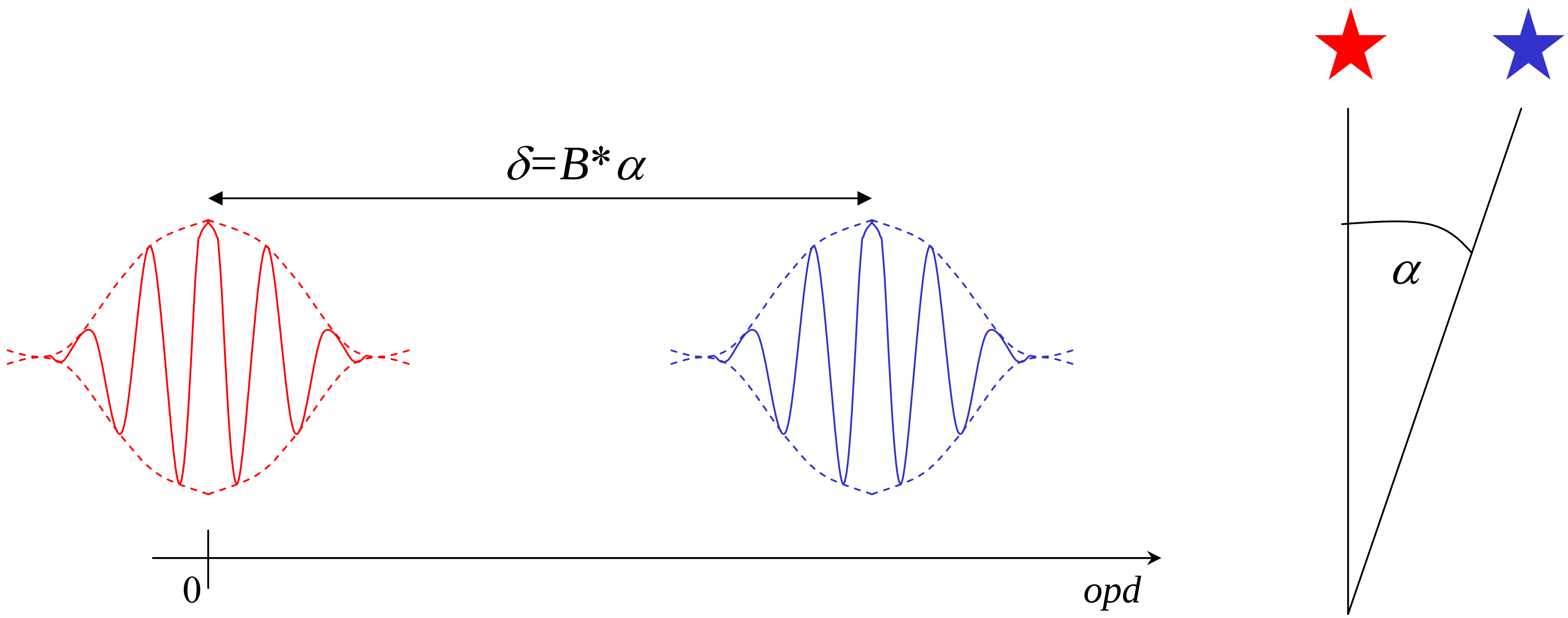


Crosstalk – Pupil Plane

- Best to coherently integrate forward and reverse scan together
  - Cancels slowly-varying part of leaked signal
- In this case $T_{scan} = 0.4t_0$ gives 1% fringe power leakage



Field of View: Co-Axial Combination



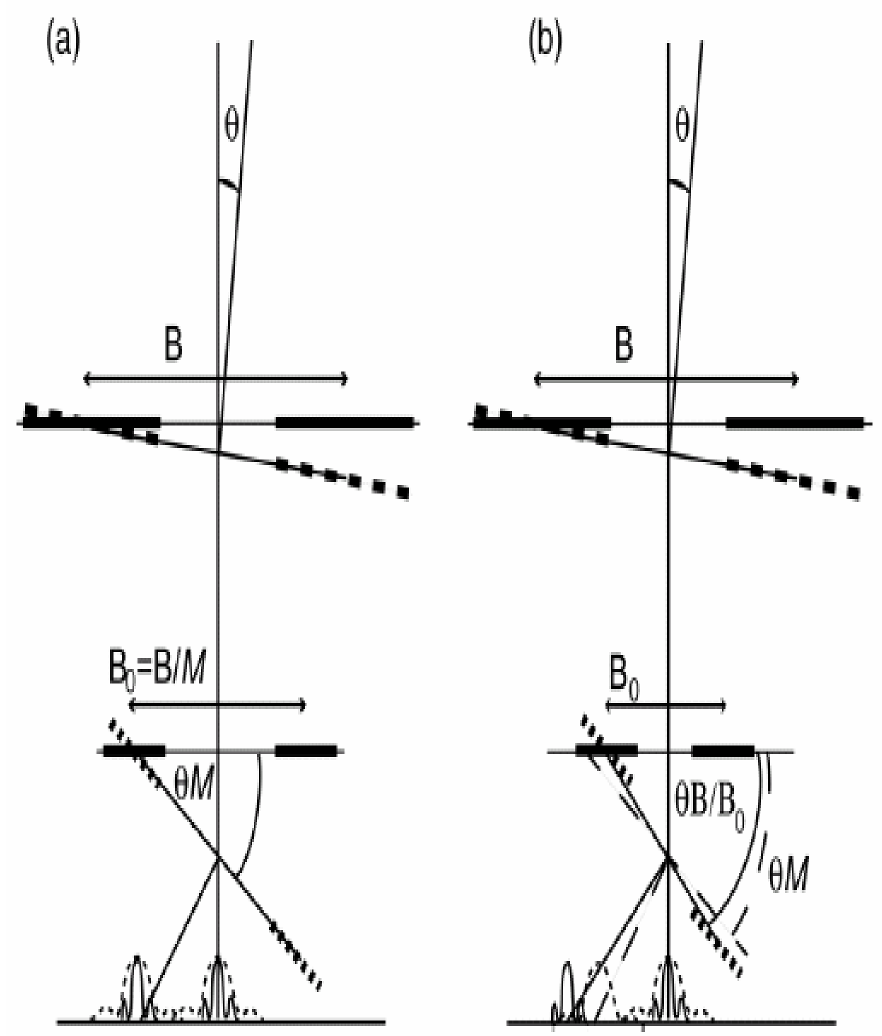
Condition for the off-axis object to contribute to the main fringe pattern: $B \times \alpha \le \frac{\lambda^2}{\Delta\lambda}$

Hence the field of view: $\alpha_{\max} = \frac{\lambda}{B} \times \frac{\lambda}{\Delta\lambda}$

FOV is product of the spatial and spectral resolutions

Golden Rule (Traub)

- FOV of an image-plane interferometer maximised when exit pupil is **scaled version** of entrance pupil
  - Entrance pupil: array of collector pupils as seen from target
  - Exit pupil: input pupil of beam combiner
- Instruments that implement this are called *homothetic mappers*
- If golden rule violated, FOV limited because white-light fringe for off-axis object doesn't coincide with centre of its light



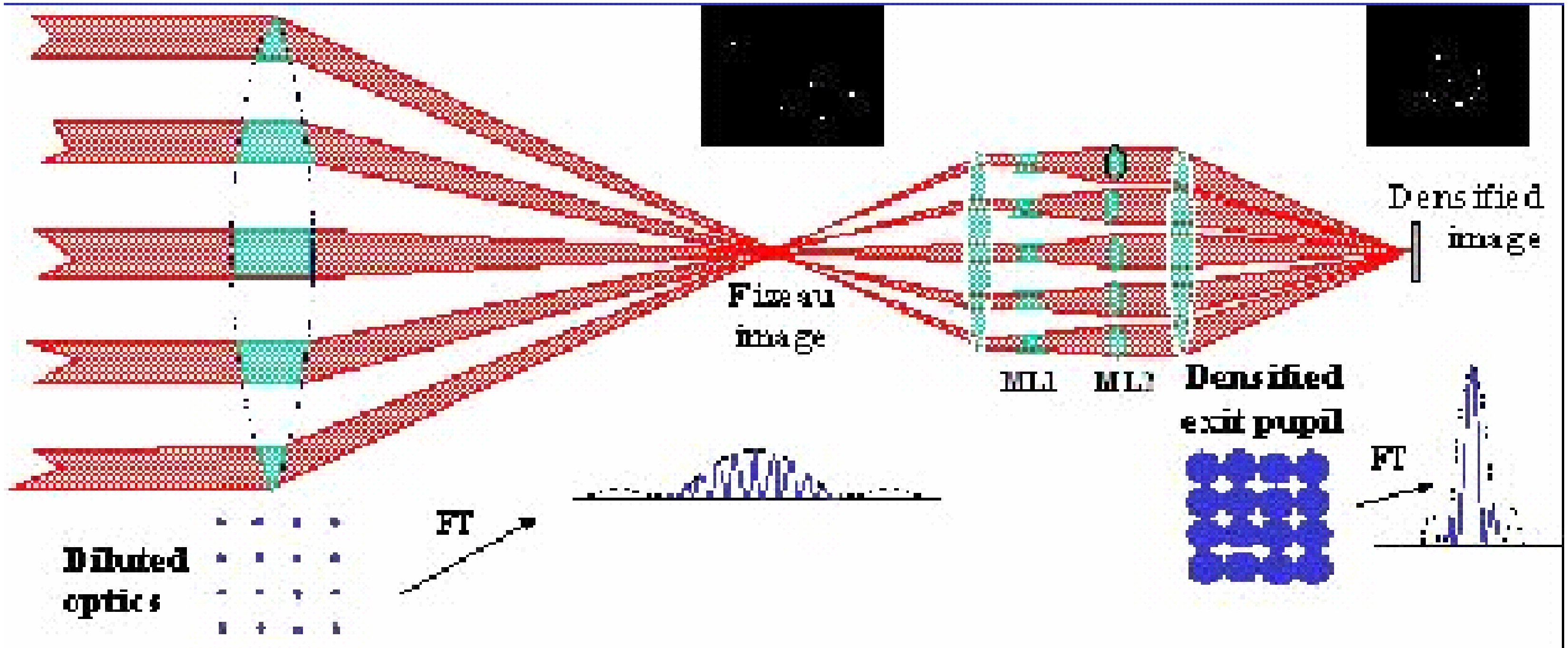
Homothetic Mapping: How To

- Easy way
  - Collectors on common mount
  - e.g. aperture masking, LBT

- Hard way
  - Collectors on independent mounts
  - Active relay optics to continuously adjust pupil mapping as Earth rotates
  - e.g. ……

Densified Pupils: "Hypertelescopes"

- Violate golden rule to concentrate light in fewer pixels
- Reduced field of view
- Aimed at direct imaging i.e. not via visibility measurement
  - Fringe pattern approximates target field convolved with compact PSF

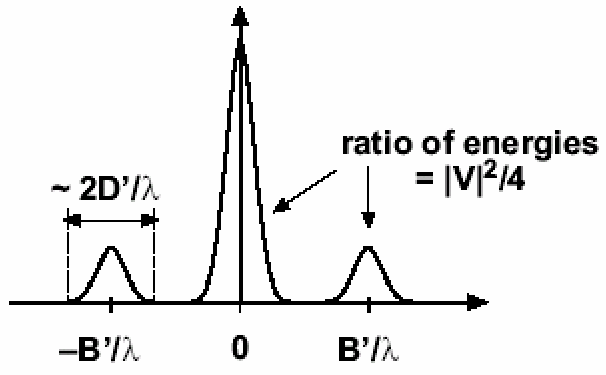


FOV Limits

- Need to consider which of following give rise to FOV lower limit for each baseline of each observation:
  - FOV of collectors
  - Isoplanatic patch
  - FOV of interferometer optical train
  - Beam Combiner configuration – OPD effects
  - Spatial Filters
- For a dilute-aperture array, the above list is **usually** in order of decreasing FOV
  - Exchange the last two for lower spectral resolutions
- Remember that only the Fourier components corresponding to your projected baselines are sampled
  - Cannot image fields with many filled pixels unless many collectors

Interferometric (coherent) versus incoherent FOV

- In general, FOV over which target will contribute to measured fringe power (correlated flux) $\neq$ FOV for detected incoherent flux
- Visibility amplitude est. is ratio of coherent to incoherent flux:



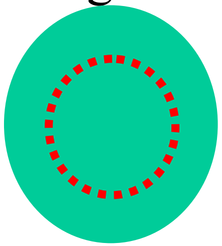
- Incoherent field $\geq$ coherent (interferometric) field
  - Each part of field can contribute just DC signal, or both DC and fringe power, or not at all
- Centres of coherent and incoherent fields may not coincide precisely e.g. if target has non-uniform colour
  - Centre of coherent field related to fringe-tracking centre
  - Centre of incoherent field related to guiding centre

FOV Limits (again)

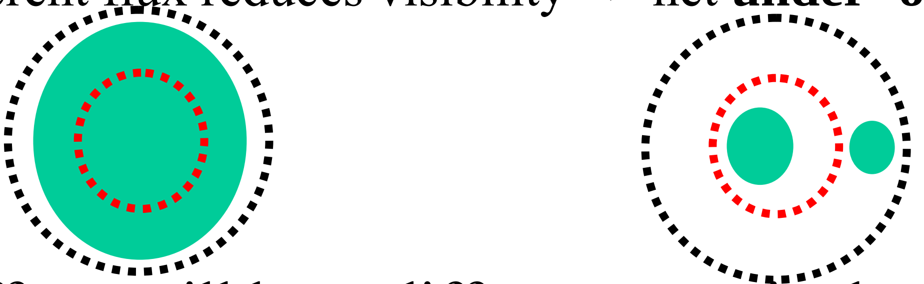
- Need to consider which of following give rise to FOV lower limit for each baseline of each observation:
  - FOV of collectors – limits incoherent field
  - Isoplanatic patch – limits coherent field
  - FOV of interferometer optical train – limits incoherent field
  - Beam Combiner configuration (OPD effects) – limits coherent field
  - Spatial Filters – limits incoherent field
- For a dilute-aperture array, the above list is **usually** in order of decreasing FOV
  - Exchange the last two for lower spectral resolutions

Restricted FOV effects

- Some examples:
  - coherent FOV = incoherent FOV < target size
    Interferometer “sees” smaller target => **overestimates** visibility



  - coherent FOV < target size < incoherent FOV
    Extra incoherent flux reduces visibility => net **under- or overestimate**



- Remember effects will have different magnitude on different baselines, so data need careful interpretation

Summary: Pupil planes versus Image planes

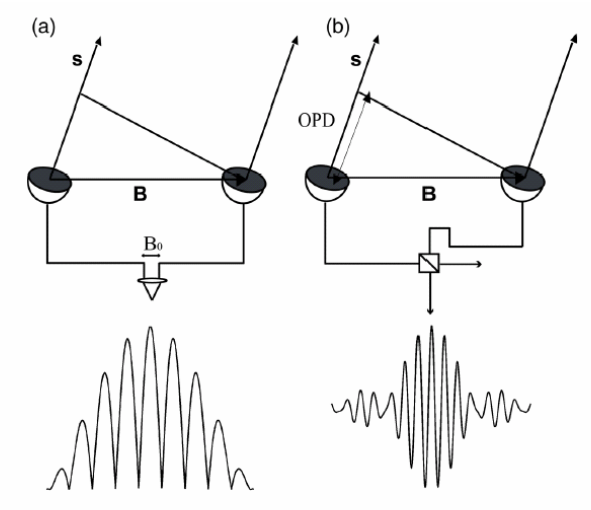


Image Plane Pros

- Allows homothetic configuration to access larger fields

Pupil Plane Pros:

- Fewer detector pixels needed

Image Plane Cons:

- Need large format detectors
- Usually need highly anamorphic optics to realise spectral resolution

Pupil Plane Cons:

- Need fast modulators, fast detectors
- Cross-talk
- Potentially many optical components (not with IO or contacted optics)